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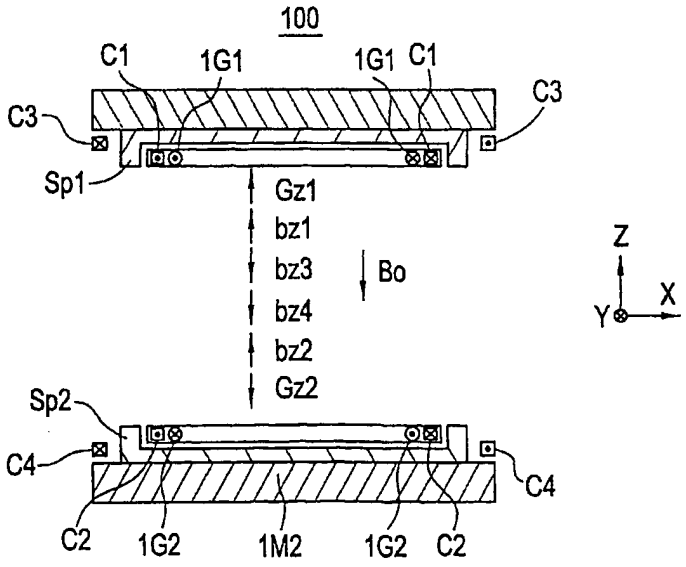
(54) Second-order static magnetic field error correcting method and Mri apparatus

(57) For the purpose of reducing second-order static magnetic field components in an MRI apparatus, a first circular loop coil (C1) and a second circular loop coil (C2) are disposed at positions spaced in a static magnetic field (B0) direction to be symmetrical with respect to a center (Z0) of an imaging region of an MRI apparatus (100). Similarly, a third circular loop coil (C3) and a fourth circular loop coil (C4) are disposed. A first corrective magnetic field (bz1) and a second corrective magnetic field (bz2) are generated in the same direction by the first and second circular loop coils (C1) and (C2), and a third corrective magnetic field (bz3) and a fourth corrective magnetic field (bz4) are generated in the same direction and opposite to the first corrective magnetic field (bz1) by the third and fourth circular loop coils (C3) and (C4). The second-order components of the static magnetic field (B0) are corrected by the corrective magnetic fields (bz1 — bz4).

FIG. 2



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Description

[0001] The present invention relates to a second-order static magnetic field correcting method and an MRI (magnetic resonance imaging) apparatus, and more particularly to a second-order static magnetic field correcting method for correcting second-order static magnetic field components to improve homogeneity in an MRI apparatus and an MRI apparatus that can implement the method.

[0002] The static magnetic field of an MRI apparatus should be homogeneous. Homogeneity of the static magnetic field is achieved by mechanical shimming or by adding small pieces of magnet, iron or the like.

[0003] A metal mass (e.g., an automobile) moving near the MRI apparatus or an environment change (e.g., a change in temperature) varies the static magnetic field, and second-order static magnetic field components are generated.

[0004] Pulse sequences that observe gradient echoes, such as one according to GRASS (gradient recalled acquisition in the steady state) or SPGR (spoiled GRASS), are very sensitive to the static magnetic field components, and the generation of the second-order static magnetic field components leads to degradation of image quality.

[0005] It is therefore an object of the present invention to provide a second-order static magnetic field correcting method for correcting second-order static magnetic field components to improve homogeneity and an MRI apparatus that can implement the method.

[0006] In accordance with its first aspect, the present invention provides a second-order static magnetic field correcting method characterized in: disposing a first circular loop coil and a second circular loop coil at positions spaced in a static magnetic field direction to be symmetrical with respect to a center of an imaging region of an MRI apparatus; disposing a third circular loop coil and a fourth circular loop coil having a larger diameter than that of said first and second circular loop coils at positions spaced in the static magnetic field direction to be symmetrical with respect to the center of said imaging region; generating a first corrective magnetic field and a second corrective magnetic field in the same direction by said first and second circular loop coils; and generating a third corrective magnetic field and a fourth corrective magnetic field in the same direction and opposite to said first corrective magnetic field by said third and fourth circular loop coils; thereby correcting second-order static magnetic field components in the static magnetic field direction.

[0007] In this specification, by a "second order" is meant a quadric function of a position in a static magnetic field direction. By a "zeroth order" is meant independence of the position in the static magnetic field direction. Furthermore, by a "first order" is meant a linear function of the static magnetic field direction.

[0008] In the second-order static magnetic field correcting method of the first aspect, since the direction of the first and second corrective magnetic fields generated by the first and second circular loop coils is opposite to the direction of the third and fourth corrective magnetic fields generated by the third and fourth circular loop coils, zeroth-order corrective magnetic field components in the static magnetic field direction can cancel one another, and thus the zeroth-order static magnetic field components are not affected. On the other hand, since the zeroth-order corrective magnetic field components are independent of the second-order corrective magnetic field components, the second-order corrective magnetic field components remain even after the zeroth-order corrective magnetic field components have canceled one another. Therefore, the second-order corrective magnetic field components can cancel the second-order static magnetic field components, and homogeneity of the static magnetic field can be improved.

[0009] Since the first and second corrective magnetic fields are in the same direction, these fields will not generate first corrective magnetic field components. Similarly, since the third and fourth corrective magnetic fields are in the same direction, these fields will not generate first corrective magnetic field components.

[0010] In accordance with its second aspect, the present invention provides the second-order static magnetic field correcting method of the aforementioned configuration, characterized in that said first and second circular loop coils are disposed substantially coplanar with gradient coils for the static magnetic field direction and outside said gradient coils.

[0011] In the second-order static magnetic field correcting method of the second aspect, since the first and second circular loop coils are disposed substantially coplanar with gradient coils for the static magnetic field direction and outside the gradient coils, symmetry with respect to the gradient coils for the static magnetic field direction is conserved; moreover, the first and second corrective magnetic fields are in the same direction, and therefore the gradient magnetic fields are not substantially affected. Furthermore, since circular loop coils, which have no return path, exhibit better linearity than that of gradient coils having return paths, linearity of the gradient magnetic fields is not substantially affected.

[0012] In accordance with its third aspect, the present invention provides the second-order static magnetic field correcting method of the aforementioned configuration, characterized in that said third and fourth circular loop coils are disposed surrounding magnetism conditioning plates.

[0013] In the second-order static magnetic field correcting method of the third aspect, since the third and fourth circular loop coils are disposed surrounding magnetism conditioning plates, the space for installing the circular loop coils can be easily secured. Moreover, there is no need for concern about coupling with the gradient coils.

[0014] If the third and fourth circular loop coils are dis-

posed so that the conditions of Helmholtz coils are fulfilled, second-order corrective magnetic field components generated by the third and fourth circular loop coils can be ignored. Therefore, in order to cancel second-order static magnetic field components, only the second-order corrective magnetic field components generated by the first and second circular loop coils need to be adjusted, and thus the adjustment can be done easily.

[0015] In accordance with its fourth aspect, the present invention provides the second-order static magnetic field correcting method of the aforementioned configuration, characterized in that at least one of the ratio of electric currents and the turns ratio of said first through fourth circular loop coils is determined so that zeroth-order corrective magnetic field components in the static magnetic field direction cancel one another.

[0016] In the second-order static magnetic field correcting method of the fourth aspect, since the ratio of electric currents or the turns ratio is adjusted so that the zeroth-order corrective magnetic field components are canceled out, only the electric current values need to be adjusted to cancel the second-order static magnetic field components while maintaining the ratio of corrective electric currents, and thus the adjustment can be done easily.

[0017] In accordance with its fifth aspect, the present invention provides a second-order static magnetic field correcting method, characterized in: disposing three RF probes at different positions in a static magnetic field direction of an MRI apparatus, each of which probes has a small phantom capable of emitting an FID (free induction decay) signal and a small coil combined; transmitting RF pulses from said RF probes and receiving FID signals at a time when a magnetic field variation is to be measured; determining frequencies f1, f2 and f3 from the FID signals; determining a second-order static magnetic field component β2 by solving the following simultaneous equations:

$$f_1=\beta_0+\beta_1\cdot r_1+\beta_2\cdot r_1^2$$

$$f_2=\beta_0+\beta_1\cdot r_2+\beta_2\cdot r_2^2,$$

$$f_3=\beta_0+\beta_1\cdot r_3+\beta_2\cdot r_3^2$$

wherein the positions of said RF probes are designated by r1, r2 and r3; and adjusting corrective magnetic fields based on said second-order static magnetic field component β2.

[0018] In the second-order static magnetic field correcting method of the fifth aspect, since corrective magnetic fields are adjusted by disposing RF probes to measure the second-order magnetic field components at an appropriate time, the correction can be suitably achieved.

[0019] In accordance with its sixth asp ct, the present invention provides a second-order static magnetic field correcting method, characterized in: disposing three RF probes at different positions in a static magnetic field direction of an MRI apparatus, each of which probes has a small phantom capable of emitting an FID signal and a small coil combined; transmitting RF pulses from said RF probes and receiving FID signals at a time when a reference magnetic field is to be measured; determining reference frequencies f1r, f2r and f3r from the FID signals; transmitting RF pulses from said RF probes and receiving FID signals at a time when a magnetic field variation is to be measured; determining frequencies f1, f2 and f3 from the FID signals; determining a second-order magnetic field variation α2 by solving the following simultaneous equations:

$$f_1-f_{1r}=\alpha_0+\alpha_1\cdot r_1+\alpha_2\cdot r_1^2$$

$$f_2-f_{2r}=\alpha_0+\alpha_1\cdot r_2+\alpha_2\cdot r_2^2,$$

$$f_3-f_{3r}=\alpha_0+\alpha_1\cdot r_3+\alpha_2\cdot r_3^2$$

wherein the positions of said RF probes are designated by r1, r2 and r3; and adjusting corrective magnetic fields based on said second-order magnetic field variation α2.

[0020] In the second-order static magnetic field correcting method of the sixth aspect, since corrective magnetic fields are adjusted by disposing RF probes to measure a reference static magnetic field as a reference frequency at an appropriate time, disposing the RF probes to measure the static magnetic field as a frequency at a later appropriate time, and measuring a second-order magnetic field variation from their difference, the correction can be suitably achieved.

[0021] In accordance with its seventh aspect, the present invention provides the second-order static magnetic field correcting method of the aforementioned configuration, characterized in: determining a zeroth-order magnetic field variation α0, and adjusting a transmit frequency for an RF pulse and a receive detection frequency for an NMR signal based on said zeroth-order magnetic field variation α0.

[0022] In the second-order static magnetic field correcting method of the seventh aspect, a zeroth-order static magnetic field variation can be compensated by correction of the transmit frequency for an RF pulse and the receive detection frequency for an NMR signal.

[0023] In accordance with its eighth aspect, the present invention provides the second-order static magnetic field correcting method of the aforementioned configuration, characterized in: determining a first-order magnetic field variation α1, and adjusting a gradient electric current based on said first-order magnetic field

variation $\alpha 1$.

[0024] In the second-order static magnetic field correcting method of the eighth aspect, a first-order static magnetic field variation can be compensated by correction of the gradient electric current.

[0025] In accordance with its ninth aspect, the present invention provides the second-order static magnetic field correcting method of the aforementioned configuration, characterized in that said MRI apparatus is an open-type MRI apparatus that generates the static magnetic field in a vertical direction.

[0026] In the second-order static magnetic field correcting method of the ninth aspect, homogeneity of the static magnetic field in an open-type MRI apparatus in which homogeneity of the magnetic field is obtained by mechanical shimming or by adding small pieces of magnet, iron or the like can be improved.

[0027] In accordance with its tenth aspect, the present invention provides an MRI apparatus characterized in comprising: a first circular loop coil and a second circular loop coil disposed at positions spaced in a static magnetic field direction to be symmetrical with respect to a center of an imaging region, for generating a first corrective magnetic field and a second corrective magnetic field in the same direction; a third circular loop coil and a fourth circular loop coil having a larger diameter than that of said first and second circular loop coils, disposed at positions spaced in the static magnetic field direction to be symmetrical with respect to the center of said imaging region, for generating a third corrective magnetic field and a fourth corrective magnetic field in the same direction and opposite to said first corrective magnetic field; and circular loop coil driving means for applying corrective electric currents to said first through fourth circular loop coils to generate said first through fourth corrective magnetic fields.

[0028] In the MRI apparatus of the tenth aspect, the second-order static magnetic field correcting method as described regarding the first aspect can be suitably implemented.

[0029] In accordance with its eleventh aspect, the present invention provides the MRI apparatus of the aforementioned configuration, characterized in that said first and second circular loop coils are disposed substantially coplanar with gradient coils for the static magnetic field direction and outside said gradient coils.

[0030] In the MRI apparatus of the eleventh aspect, the second-order static magnetic field correcting method as described regarding the second aspect can be suitably implemented.

[0031] In accordance with its twelfth aspect, the present invention provides the MRI apparatus of the aforementioned configuration, characterized in that said third and fourth circular loop coils are disposed surrounding magnetism conditioning plates.

[0032] In the MRI apparatus of the twelfth aspect, the second-order static magnetic field correcting method as described regarding the third aspect can be suitably implemented.

[0033] In accordance with its thirteenth aspect, the present invention provides the MRI apparatus of the aforementioned configuration, characterized in that at least one of the ratio of electric currents and the turns ratio of said first through fourth circular loop coils is determined so that zeroth-order corrective magnetic field components in the static magnetic field direction cancel one another.

[0034] In the MRI apparatus of the thirteenth aspect, the second-order static magnetic field correcting method as described regarding the fourth aspect can be suitably implemented.

[0035] In accordance with its fourteenth aspect, the present invention provides the MRI apparatus of the aforementioned configuration, characterized in comprising: frequency acquiring means for, under the condition that three RF probes are disposed at different positions in the static magnetic field direction, each of which probes has a small phantom capable of emitting an FID signal and a small coil combined, transmitting RF pulses from said RF probes and receiving FID signals, and determining frequencies f1, f2 and f3 from the FID signals; and corrective magnetic field adjusting means for determining a second-order static magnetic field component $\beta 2$ by solving the following simultaneous equations:

$$f_1=\beta_0+\beta_1 \cdot r_1+\beta_2 \cdot r_1^2$$

$$f_2=\beta_0+\beta_1 \cdot r_2+\beta_2 \cdot r_2^2,$$

$$f_3=\beta_0+\beta_1 \cdot r_3+\beta_2 \cdot r_3^2$$

wherein the positions of said RF probes are designated by r1, r2 and r3, and adjusting the corrective magnetic fields based on said second-order static magnetic field component $\beta 2$.

[0036] In the MRI apparatus of the fourteenth aspect, the second-order static magnetic field correcting method as described regarding the fifth aspect can be suitably implemented.

[0037] In accordance with its fifteenth aspect, the present invention provides the MRI apparatus of the aforementioned configuration, characterized in comprising: reference frequency acquiring means for, under the condition that three RF probes are disposed at different positions in the static magnetic field direction, each of which probes has a small phantom capable of emitting an FID signal and a small coil combined, transmitting RF pulses from said RF probes and receiving FID signals at a time when a reference magnetic field is to be measured, and determining reference frequencies f1r, f2r and f3r from the FID signals; frequency acquiring means for, under the condition that three RF probes are

disposed at different positions in the static magnetic field direction, each of which probes has a small phantom capable of emitting an FID signal and a small coil combined, transmitting RF pulses from said RF probes and receiving FID signals at a time when a magnetic field variation is to be measured, and determining frequencies f1, f2 and f3 from the FID signals; and second-order magnetic field variation compensating means for determining a second-order magnetic field variation α2 by solving the following simultaneous equations:

$$f_1 - f_{1r} = \alpha_0 + \alpha_1 \cdot r_1 + \alpha_2 \cdot r_1^2$$

$$f_2 - f_{2r} = \alpha_0 + \alpha_1 \cdot r_2 + \alpha_2 \cdot r_2^2,$$

$$f_3 - f_{3r} = \alpha_0 + \alpha_1 \cdot r_3 + \alpha_2 \cdot r_3^2$$

wherein the positions of said RF probes are designated by r1, r2 and r3, and adjusting the corrective magnetic fields based on said second-order magnetic field variation α2.

[0038] In the MRI apparatus of the fifteenth aspect, the second-order static magnetic field correcting method as described regarding the sixth aspect can be suitably implemented.

[0039] In accordance with its sixteenth aspect, the present invention provides the MRI apparatus of the aforementioned configuration, characterized in comprising zeroth-order magnetic field variation compensating means for determining a zeroth-order magnetic field variation α0, and adjusting a transmit frequency for an RF pulse and a receive detection frequency for an NMR signal based on said zeroth-order magnetic field variation α0.

[0040] In the MRI apparatus of the sixteenth aspect, the second-order static magnetic field correcting method as described regarding the seventh aspect can be suitably implemented.

[0041] In accordance with its seventeenth aspect, the present invention provides the MRI apparatus of the aforementioned configuration, characterized in comprising first-order magnetic field variation compensating means for determining a first-order magnetic field variation α1, and adjusting a gradient electric current based on said first-order magnetic field variation α1.

[0042] In the MRI apparatus of the seventeenth aspect, the second-order static magnetic field correcting method as described regarding the eighth aspect can be suitably implemented.

[0043] In accordance with its eighteenth aspect, the present invention provides the MRI apparatus of the aforementioned configuration, characterized in that said MRI apparatus is an open-type MRI apparatus that generates the static magnetic field in a vertical direction.

[0044] In the MRI apparatus of the eighteenth aspect, the second-order static magnetic field correcting method as described regarding the ninth aspect can be suitably implemented.

[0045] According to the second-order static magnetic field correcting method and the MRI apparatus of the present invention, second-order static magnetic field components can be reduced to improve homogeneity of the static magnetic field in an MRI apparatus.

[0046] Further objects and advantages of the present invention will be apparent from the following description of the preferred embodiments of the invention as illustrated in the accompanying drawings, in which:

Fig. 1 is a main portion cross-sectional view illustrating an MRI apparatus in accordance with one embodiment of the present invention.

Fig. 2 is a view for explanation illustrating magnetic fields in the static magnetic field direction.

Fig. 3 is a main portion cross-sectional view showing the condition in measuring the static magnetic field of an MRI apparatus in accordance with one embodiment of the present invention.

Fig. 4 is a cross-sectional view illustrating one example of an RF probe in accordance with the present invention.

Fig. 5 is a configuration block diagram showing an MRI apparatus in accordance with one embodiment of the present invention.

Fig. 6 is a block diagram showing one example of an NMR signal transmitting/receiving circuit in accordance with the present invention.

Fig. 7 is a flow chart showing the operation of second-order static magnetic field measuring processing in accordance with the present invention.

Fig. 8 is a flow chart continued from Fig. 7.

Fig. 9 is a flow chart showing the operation of reference magnetic field measuring processing in accordance with the present invention.

Fig. 10 is a flow chart showing the operation of magnetic field compensating processing in accordance with the present invention.

Fig. 1 is a major portion cross-sectional view illustrating an MRI apparatus 100 in accordance with one embodiment of the present invention.

[0047] The MRI apparatus 100 is an open-type MRI apparatus that generates the static magnetic field in the vertical direction by permanent magnets 1M1 and 1M2

disposed above and below and facing each other.

[0048] On the surfaces of the permanent magnets 1M1 and 1M2 are disposed respective magnetism conditioning plates Sp1 and Sp2 for creating an imaging region having a homogeneous static magnetic field inside a receiving coil 1 R capable of containing therein a subject.

[0049] The permanent magnets 1M1 and 1M2, magnetism conditioning plates Sp1 and Sp2, base yokes By and pole yokes Py constitute a magnetic circuit.

[0050] It should be noted that superconductive magnets may be employed instead of the permanent magnets 1M1 and 1M2.

[0051] On the surfaces of the magnetism conditioning plates Sp1 and Sp2 are disposed respective gradient coils 1G1 and 1G2 for generating gradient magnetic fields in the static magnetic field.

[0052] Inside the gradient coils 1G1 and 1G2, transmitting coils 1T are disposed for transmitting RF pulses for exciting spins of atomic nuclei within the subject.

[0053] The receiving coil 1R is a coil for receiving NMR signals emanating from the subject.

[0054] A first circular loop coil C1 is disposed on the same substrate as that for the gradient coil 1G1, and outside the gradient coil 1G1.

[0055] A second circular loop coil C2 is disposed on the same substrate as that for the gradient coil 1G2, and outside the gradient coil 1G2.

[0056] The first and second circular loop coils C1 and C2 have the same diameter, and are disposed at positions spaced in the static magnetic field direction to be symmetrical with respect to a center Z0 of the imaging region.

[0057] A third circular loop coil C3 is disposed surrounding the magnetism conditioning plate Sp1.

[0058] A fourth circular loop coil C4 is disposed surrounding the magnetism conditioning plate Sp2.

[0059] The third and fourth circular loop coils C3 and C4 have the same diameter, and are disposed at positions spaced in the static magnetic field direction to be symmetrical with respect to the center Z0 of the imaging region to fulfill the conditions of Helmholtz coils.

[0060] As shown in Fig. 2, the gradient coil 1G1 generates a gradient magnetic field Gz1. The gradient coil 1G2 generates a gradient magnetic field Gz2 in a direction opposite to the gradient magnetic field Gz1. Thus, a gradient magnetic field is generated in the static magnetic field direction.

[0061] The first circular loop coil C1 generates a first corrective magnetic field bz1. The second circular loop coil C2 generates a second corrective magnetic field bz2 in the same direction as the first corrective magnetic field bz1.

[0062] The third circular loop coil C3 generates a third corrective magnetic field bz3 in a direction opposite to the first corrective magnetic field bz1. The fourth circular loop coil C4 generates a fourth corrective magnetic field bz4 in the same direction as the third corrective magnetic field bz3.

[0063] Fig. 3 is a main portion cross-sectional view illustrating the condition in which three RF probes 1P1, 1P2 and 1P3 for measuring the magnetic field are disposed at three positions on an axis Z in the static magnetic field direction passing through the center Z0 of the imaging region.

[0064] In this specification, the disposed positions of the RF probes 1P1, 1P2 and 1P3 are designated by r1, r2 and r3.

[0065] Fig. 4 is an explanatory cross-sectional view illustrating the RF probes 1P1, 1P2 and 1P3.

[0066] The RF probes 1P1, 1P2 and 1P3 each has a configuration in which a small phantom Ft enclosing NaCl solution or $CuSo_4$ solution capable of emitting an FID signal, and a small coil Co surrounding the small phantom Ft are combined.

[0067] Fig. 5 is a configuration block diagram showing the MRI apparatus 100.

[0068] In the MRI apparatus 100, a magnet assembly 1 is configured to comprise the permanent magnets 1M1 and 1M2, receiving coil 1R, gradient coil 1G, (the gradient coil 1G consists of X-axis gradient coils, Y-axis gradient coils and Z-axis gradient coils 1G1 and 1G2), transmitting coils 1T, and circular loop coils C1 — C4.

[0069] The receiving coil 1R is connected to a preamplifier 5.

[0070] The gradient coil 1G is connected to a gradient coil driving circuit 3.

[0071] The transmitting coils 1T are connected to an RF power amplifier 4.

[0072] A sequence memory circuit 8 operates the gradient coil driving circuit 3 based on an imaging pulse sequence, such as one according to a spin echo technique, in response to instructions from a computer 7 to thereby generate an X-axis gradient magnetic field, Y-axis gradient magnetic field and Z-axis gradient magnetic field by the gradient coil 1G. The sequence memory circuit 8 also operates a gate modulation circuit 9 to modulate a high-frequency output signal from an RF oscillation circuit 10 into a pulsed signal of predefined timing and envelope shape. The pulsed signal is applied to the RF power amplifier 4 as an RF pulse signal, power-amplified in the RF power amplifier 4, and then applied to the transmitting coils 1T in the magnet assembly 1 to transmit the RF pulse from the transmitting coils 1T.

[0073] The preamplifier 5 amplifies an NMR signal from the subject detected at the receiving coil 1R, and inputs the signal to a phase detector 12. The phase detector 12 phase-detects the NMR signal from the preamplifier 5 employing the output from the RF oscillation circuit 10 as a receive detection signal, and supplies the phase-detected signal to an A/D converter 11. The A/D converter 11 converts the phase-detected analog signal into digital signal MR data, and inputs it to the computer 7.

[0074] The computer 7 performs an image reconstruction operation on the MR data to produce an MR

image. The MR image is displayed on a display device 6. The computer 7 is also responsible for overall control such as receiving information input from an operating console 13.

[0075] Moreover, the computer 7 controls circular loop coil driving circuits 17 and 18 via a digital processing circuit 19 to apply corrective electric currents to the circular loop coils C1 — C4 for generating the corrective magnetic fields bz1 — bz4, thereby correcting second-order static magnetic field components to improve homogeneity of the static magnetic field.

[0076] In measuring the magnetic field, the RF probes 1P1, 1P2 and 1P3 are placed and connected to the computer 7 via an NMR signal transmitting/receiving circuit 15 and a digital processing circuit 16.

[0077] The RF probes 1P1, 1P2 and 1P3, NMR signal transmitting/receiving circuit 15 and digital processing circuit 16 constitute a static magnetic field measuring auxiliary apparatus 200.

[0078] When the static magnetic field measuring auxiliary apparatus 200 is connected, the computer 7 executes second-order static magnetic field measuring processing, reference magnetic field measuring processing or magnetic field compensating processing. The second-order static magnetic field measuring processing will be elaborated later with reference to Figs. 7 and 8. The reference magnetic field measuring processing will be elaborated later with reference to Fig. 9. The magnetic field compensating processing will be elaborated later with reference to Fig. 10.

[0079] Fig. 6 is a configuration block diagram of the NMR signal transmitting/receiving circuit 15.

[0080] The NMR signal transmitting/receiving circuit 15 comprises an RF driving circuit 150 that comprises an RF oscillation circuit, gate modulation circuit and RF power amplifier; a multiplexer 151 for switching the output destination of RF pulse transmitted signals output from the RF driving circuit 150; transmission/reception switching switches 152, 153 and 154 for switching between transmission of the RF pulse transmitted signals to the RF probes 1P1, 1P2 and 1P3 and reception of FID received signals from the RF probes 1P1, 1P2 and 1P3; preamplifiers 155, 156 and 157 for amplifying the FID received signals from the RF probes 1P1, 1P2 and 1P3; an adder 158 for adding the FID received signals amplified at the preamplifiers 155, 156 and 157; a down converter 159 for converting the frequency of the FID received signals to the intermediate frequency band; and an intermediate frequency amplifier 160 for amplifying the FID signals frequency-converted to the intermediate frequency band.

[0081] The digital processing circuit 16 operates the NMR signal transmitting/receiving circuit 15 in response to instructions from the computer 7, and converts the FID signals into digital data and inputs them to the computer 7.

[0082] Fig. 7 is a flow chart showing the operation of the second-order static magnetic field measuring processing by the MRI apparatus 100. The second-order static magnetic field measuring processing is activated by instructions from an operator under the condition in which the static magnetic field measuring auxiliary apparatus 200 is connected and the thr e RF probes 1P1, 1P2 and 1P3 are disposed.

[0083] In Step ST0, no electric current is applied to the circular loop coils C1 — C4.

[0084] In Step ST1, an RF pulse is transmitted from one RF probe and an FID signal N_{ir} is obtained. For example, an RF pulse is transmitted from the first RF probe 1P1 and an FID signal N_{1r} is received.

[0085] In Step ST2, a phase ϕ_{ir} (t) is determined from I and Q of the FID signal N_{ir}, and the phase ϕ_{ir} (t) is differentiated by the time t to determine a reference frequency f_{ir}. For example, a reference frequency f_{1r} is determined from the FID signal N_{1r}.

[0086] In Step ST3, if the reference frequency has not been obtained for all the RF probes, the process goes back to Step ST1; otherwise goes to Step ST4. Specifically, if only the reference frequency f_{1r} at the first RF probe 1P1 has been obtained, the process goes back to Step ST1 to obtain a reference frequency f_{2r} at the second RF probe 1P2 in Steps ST1 and ST2. Moreover, if only the reference frequency f_{1r} at the first RF probe 1P1 and the reference frequency f_{2r} at the second RF probe 1P2 have been obtained, the process goes back to Step ST1 to obtain a reference frequency f_{3r} at the second RF probe 1P3 in Steps ST1 and ST2. The process then goes to Step ST4.

[0087] In Step ST4, electric currents having the same magnitude are applied to the circular loop coils C1 — C4.

[0088] In Step ST5, an RF pulse is transmitted from one RF probe and an FID signal N_i is obtained. For example, an RF pulse is transmitted from the first RF probe 1P1 and an FID signal N_1 is received.

[0089] In Step ST6, a phase ϕ_i (t) is determined from I and Q of the FID signal N_i, and the phase ϕ_i (t) is differentiated by the time t to determine a frequency f_i. For example, a frequency f_1 is determined from the FID signal N_1.

[0090] In Step ST7, if the frequency has not been obtained for all the RF probes, the process goes back to Step ST5; otherwise goes to Step ST8. Specifically, if only the frequency f_1 at the first RF probe 1P1 has been obtained, the process goes back to Step ST5 to obtain a frequency f_2 at the second RF probe 1 P2 in Steps ST5 and ST6. Moreover, if only the frequency f_1 at the first RF probe 1P1 and the frequency f_2 at the second RF probe 1P2 have been obtained, the process goes back to Step ST5 to obtain a frequency f_3 at the third RF probe 1P3 in Steps ST5 and ST6. The process then goes to Step ST8.

[0091] In Step ST8, a zeroth-order variation component α_0 (i.e., a zeroth-order static magnetic field component generated by applying the electric currents to the circular loop coils C1 — C4) is determined by solving

the following simultaneous equations:

$$f_1-f_{1r}=\alpha_0+\alpha_1\cdot r_1+\alpha_2\cdot r_1^2$$

$$f_2-f_{2r}=\alpha_0+\alpha_1\cdot r_2+\alpha_2\cdot r_2^2,$$

$$f_3-f_{3r}=\alpha_0+\alpha_1\cdot r_3+\alpha_2\cdot r_3^2$$

wherein the positions of the RF probes 1P1, 1P2 and 1P3 are designated by r1, r2 and r3.

[0092] In Step ST9, at least one of the ratio of electric currents applied to the circular loop coils C1 — C4 and the turns ratio of the circular loop coils C1 — C4 is determined so that the zeroth-order variation component α_0 becomes zero.

[0093] For example, the numbers of turns of the circular loop coils C1 — C4 are made equal, the electric current values applied to the circular loop coils C1 and C2 are made equal, the electric current values applied to the circular loop coils C3 and C4 are made equal, and the electric current ratio between the electric current value applied to the circular loop coils C1 and C2 and the electric current value applied to the circular loop coils C3 and C4 is determined. Alternatively, the electric current values applied to the circular loop coils C1 — C4 are made equal, the numbers of turns of the circular loop coils C1 and C2 are made equal, the numbers of turns of the circular loop coils C3 and C4 are made equal, and the turns ratio between the number of turns for the circular loop coils C1 and C2 and the number of turns for the circular loop coils C3 and C4 is determined. If the turns ratio is to be changed, the circular loop coils C1 — C4 should be replaced.

[0094] In Step ST11 in Fig. 8, the electric current ratio and the turns ratio determined in Step ST9 are used to apply appropriate electric currents to the circular loop coils C1 — C4.

[0095] In Steps ST12 — ST14, which are the same as Steps ST5 — ST7, the frequencies f1, f2 and f3 are determined.

[0096] In Step ST15, a second-order static magnetic field component β_2 (i.e., a second-order component of the sum of the static magnetic field B0 and the corrective magnetic fields bz1 — bz4 by the circular loop coils C1 — C4) is determined by solving the following simultaneous equations:

$$f_1=\beta_0+\beta_1\cdot r_1+\beta_2\cdot r_1^2$$

$$f_2=\beta_0+\beta_1\cdot r_2+\beta_2\cdot r_2^2.$$

$$f_3=\beta_0+\beta_1\cdot r_3+\beta_2\cdot r_3^2$$

[0097] In Step ST16, the values of electric currents to be applied to the circular loop coils C1 — C4 are determined so that the second-order static magnetic field component β_2 becomes zero. However, the electric current ratio should not be varied.

[0098] Thus, correction can be made so that the second-order static magnetic field components are reduced by applying electric currents having the electric current values determined in Step ST16 to the circular loop coils C1 — C4, and homogeneity of the static magnetic field can be improved.

[0099] Fig. 9 is a flow chart showing the operation of the reference frequency measuring processing by the MRI apparatus 100. The reference frequency measuring processing is activated by instructions from the operator when the static magnetic field B0 is in a desirable state, and under the condition that the static magnetic field measuring auxiliary apparatus 200 is connected and the three RF probes 1P1, 1P2 and 1P3 are disposed.

[0100] In Step SS1, electric currents having the electric current values determined in Step ST16 described earlier or in Step SC7 which will be described later are applied to the circular loop coils C1 — C4.

[0101] In Steps SS2 — SS4, which are the same as Steps ST1 — ST3, the reference frequencies f_{1r}, f_{2r} and f_{3r} are determined and stored.

[0102] Fig. 10 is a flow chart showing the operation of the magnetic field compensating processing by the MRI apparatus 100. The magnetic field compensating processing is activated by instructions from the operator under the condition in which the static magnetic field measuring auxiliary apparatus 200 is connected and the three RF probes 1P1, 1P2 and 1P3 are disposed.

[0103] In Step SC0, electric currents having the electric current values determined in Step ST16 described earlier or in Step SC7 which will be described later are applied to the circular loop coils C1 — C4.

[0104] In Steps SC1 — SC3, which are the same as Steps ST5 — ST7, the frequencies f_1, f_2 and f_3 are determined.

[0105] In Step SC4, a zeroth-order static magnetic field variation component α0, first-order static magnetic field variation component α1 and second-order static magnetic field variation component α2 are determined by solving the following simultaneous equations:

$$f_1-f_{1r}=\alpha_0+\alpha_1\cdot r_1+\alpha_2\cdot r_1^2$$

$$f_2-f_{2r}=\alpha_0+\alpha_1\cdot r_2+\alpha_2\cdot r_2^2.$$

$$f_3-f_{3r}=\alpha_0+\alpha_1\cdot r_3+\alpha_2\cdot r_3^2$$

[0106] In Step SC5, the oscillation frequency of the RF oscillation circuit 10 is corrected based on the ze-

roth-order static magnetic field variation α_0.

[0107] In Step SC6, the gradient electric currents for the gradient coils 1G1 and 1G2 are corrected based on the first-order static magnetic field variation component α_1. For example, offset electric currents are applied to the Z-axis gradient coils 1G1 and 1G2. A gradient magnetic field ΔG to be corrected is:

$$\Delta G = \frac{\alpha_1}{2r \cdot \gamma},$$

wherein the gyromagnetic ratio is represented as γ.

[0108] In Step SC7, the values of electric currents to be applied to the circular loop coils C1 — C4 are determined so that the second-order static magnetic field variation component $\alpha 2$ is reduced. However, the electric current ratio should not be varied.

[0109] By Steps SC5 — SC7, a variation in the static magnetic field caused by a metal mass (e.g., an automobile) moving near the MRI apparatus 100 or an environment change (e.g., a change in temperature) etc. can be restrained.

Claims

1. A second-order static magnetic field correcting method comprising the steps of:

   disposing a first circular loop coil and a second circular loop coil at positions spaced in a static magnetic field direction to be symmetrical with respect to a center of an imaging region of an MRI apparatus;
   disposing a third circular loop coil and a fourth circular loop coil having a larger diameter than that of said first and second circular loop coils at positions spaced in the static magnetic field direction to be symmetrical with respect to the center of said imaging region;
   generating a first corrective magnetic field and a second corrective magnetic field in the same direction by said first and second circular loop coils; and
   generating a third corrective magnetic field and a fourth corrective magnetic field in the same direction and opposite to said first corrective magnetic field by said third and fourth circular loop coils;
   thereby correcting second-order static magnetic field components in the static magnetic field direction.

2. A second-order static magnetic field correcting method comprising the steps of:

   disposing three RF probes at different positions in a static magnetic field dir ction of an MRI apparatus, each of which probes has a small phantom capable of emitting an FID signal and a small coil combined;
   transmitting RF pulses from said RF probes and receiving FID signals at a time when a magnetic field variation is to be measured;
   determining frequencies f1, f2 and f3 from the FID signals;
   determining a second-order static magnetic field component $\beta 2$ by solving the following simultaneous equations:

$$f_1 = \beta_0 + \beta_1 \cdot r_1 + \beta_2 \cdot r_1^2$$

$$f_2 = \beta_0 + \beta_1 \cdot r_2 + \beta_2 \cdot r_2^2,$$

$$f_3 = \beta_0 + \beta_1 \cdot r_3 + \beta_2 \cdot r_3^2$$

   wherein the positions of said RF probes are designated by r1, r2 and r3; and
   adjusting corrective magnetic fields based on said second-order static magnetic field component $\beta 2$.

3. A second-order static magnetic field correcting method comprising the steps of:

   disposing three RF probes at different positions in a static magnetic field direction of an MRI apparatus, each of which probes has a small phantom capable of emitting an FID signal and a small coil combined;
   transmitting RF pulses from said RF probes and receiving FID signals at a time when a reference magnetic field is to be measured;
   determining reference frequencies f1r, f2r and f3r from the FID signals;
   transmitting RF pulses from said RF probes and receiving FID signals at a time when a magnetic field variation is to be measured;
   determining frequencies f1, f2 and f3 from the FID signals;
   determining a second-order magnetic field variation $\alpha 2$ by solving the following simultaneous equations:

$$f_1 - f_{1r} = \alpha_0 + \alpha_1 \cdot r_1 + \alpha_2 \cdot r_1^2$$

$$f_2 - f_{2r} = \alpha_0 + \alpha_1 \cdot r_2 + \alpha_2 \cdot r_2^2,$$

$$f_3 - f_{3r} = \alpha_0 + \alpha_1 \cdot r_3 + \alpha_2 \cdot r_3^2$$

wherein the positions of said RF probes are designated by r1, r2 and r3; and
adjusting corrective magnetic fields based on said second-order magnetic field variation α2.

4. An MRI apparatus comprising:

a first circular loop coil and a second circular loop coil disposed at positions spaced in a static magnetic field direction to be symmetrical with respect to a center of an imaging region, for generating a first corrective magnetic field and a second corrective magnetic field in the same direction;
a third circular loop coil and a fourth circular loop coil having a larger diameter than that of said first and second circular loop coils, disposed at positions spaced in the static magnetic field direction to be symmetrical with respect to the center of said imaging region, for generating a third corrective magnetic field and a fourth corrective magnetic field in the same direction and opposite to said first corrective magnetic field; and
a circular loop coil driving device for applying corrective electric currents to said first through fourth circular loop coils to generate said first through fourth corrective magnetic fields.

5. The MRI apparatus of claim 4, wherein said first and second circular loop coils are disposed substantially coplanar with gradient coils for the static magnetic field direction and outside said gradient coils.

6. The MRI apparatus of claim 4, wherein said third and fourth circular loop coils are disposed surrounding magnetism conditioning plates.

7. The MRI apparatus of claim 4, wherein at least one of the ratio of electric currents and the turns ratio of said first through fourth circular loop coils is determined so that zeroth-order corrective magnetic field components in the static magnetic field direction cancel one another.

8. The MRI apparatus of claim 4, further comprising:

a frequency acquiring device for, under the condition that three RF probes are disposed at different positions in the static magnetic field direction, each of which probes has a small phantom capable of emitting an FID signal and a small coil combined, transmitting RF pulses from said RF probes and receiving FID signals, and determining frequencies f1, f2 and f3 from the FID signals; and
a corrective magnetic field adjusting device for determining a second-order static magnetic field component β2 by solving the following simultaneous equations:

$$f_1=\beta_0+\beta_1\cdot r_1+\beta_2\cdot r_1^2$$

$$f_2=\beta_0+\beta_1\cdot r_2+\beta_2\cdot r_2^2,$$

$$f_3=\beta_0+\beta_1\cdot r_3+\beta_2\cdot r_3^2$$

wherein the positions of said RF probes are designated by r1, r2 and r3, and adjusting the corrective magnetic fields based on said second-order static magnetic field component β2.

9. The MRI apparatus of claim 4, further comprising:

a reference frequency acquiring device for, under the condition that three RF probes are disposed at different positions in the static magnetic field direction, each of which probes has a small phantom capable of emitting an FID signal and a small coil combined, transmitting RF pulses from said RF probes and receiving FID signals at a time when a reference magnetic field is to be measured, and determining reference frequencies f1r, f2r and f3r from the FID signals;
a frequency acquiring device for, under the condition that three RF probes are disposed at different positions in the static magnetic field direction, each of which probes has a small phantom capable of emitting an FID signal and a small coil combined, transmitting RF pulses from said RF probes and receiving FID signals at a time when a magnetic field variation is to be measured, and determining frequencies f1, f2 and f3 from the FID signals; and
a second-order magnetic field variation compensating device for determining a second-order magnetic field variation α2 by solving the following simultaneous equations:

$$f_1-f_{1r}=\alpha_0+\alpha_1\cdot r_1+\alpha_2\cdot r_1^2$$

$$f_2-f_{2r}=\alpha_0+\alpha_1\cdot r_2+\alpha_2\cdot r_2^2,$$

$$f_3-f_{3r}=\alpha_0+\alpha_1\cdot r_3+\alpha_2\cdot r_3^2$$

wherein the positions of said RF probes are designated by r1, r2 and r3, and adjusting the corrective magnetic fields based on said second-order magnetic field variation α2.

10. The MRI apparatus of claim 4, wherein said MRI apparatus is an open-type MRI apparatus that generates the static magnetic field in a vertical direction.

FIG. 1

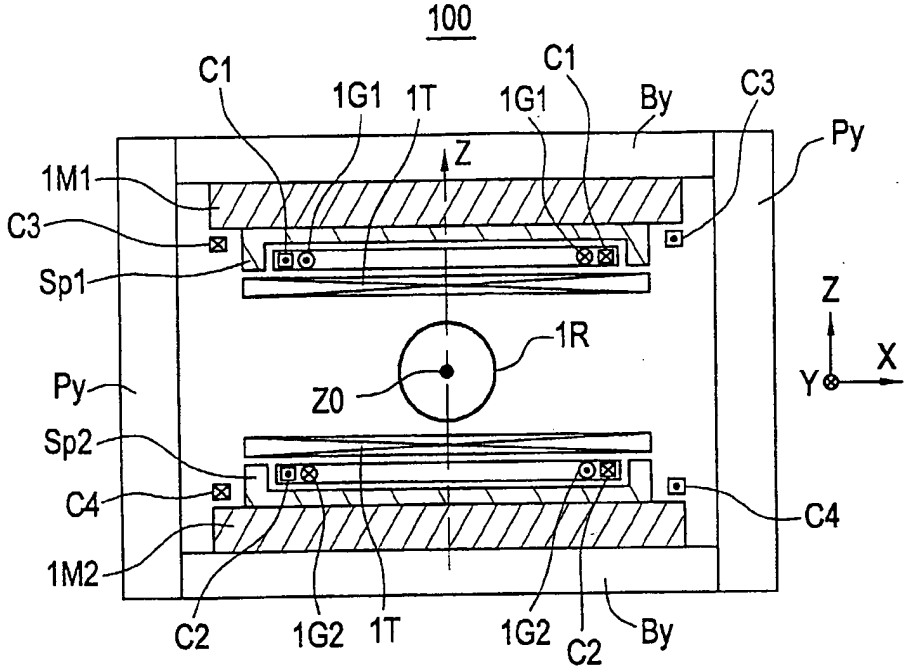

100
C1
1G1
1T
1G1
C1
By
C3
Py
Z
1M1
C3
Sp1
1R
Z0
Py
Sp2
C4
C4
1M2
C2
1G2
1T
1G2
C2
By
Z
Y
X

FIG. 2

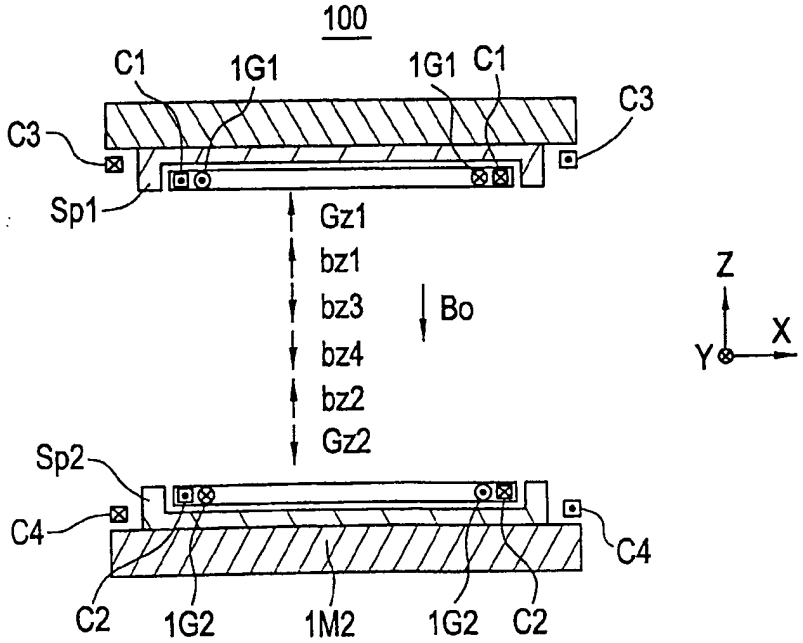
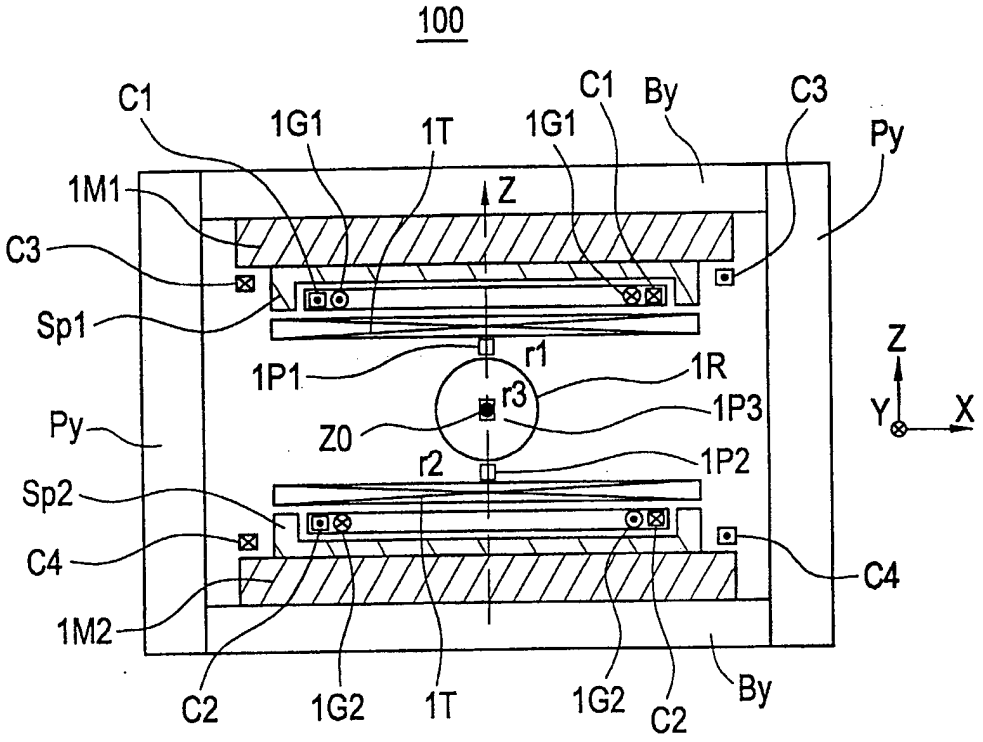

100
C1
1G1
1G1
C1
C3
C3
Sp1
Gz1
bz1
bz3
Bo
bz4
bz2
Gz2
Z
Y
X
Sp2
C4
C4
C2
1G2
1M2
1G2
C2

FIG. 3


100
C1
1G1
1T
1G1
C1
By
C3
Py
1M1
Z
C3
Sp1
1P1
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1R
r3
1P3
Z0
r2
1P2
Py
Sp2
C4
C4
1M2
C2
1G2
1T
1G2
C2
By
Z
Y
X

FIG. 4

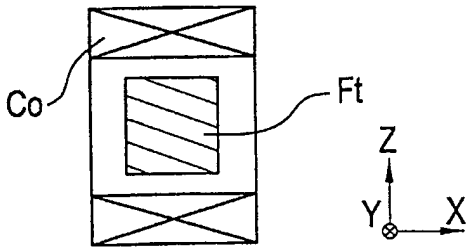

1P1, 1P2, 1P3
Co
Ft
Z
Y
X

FIG. 5

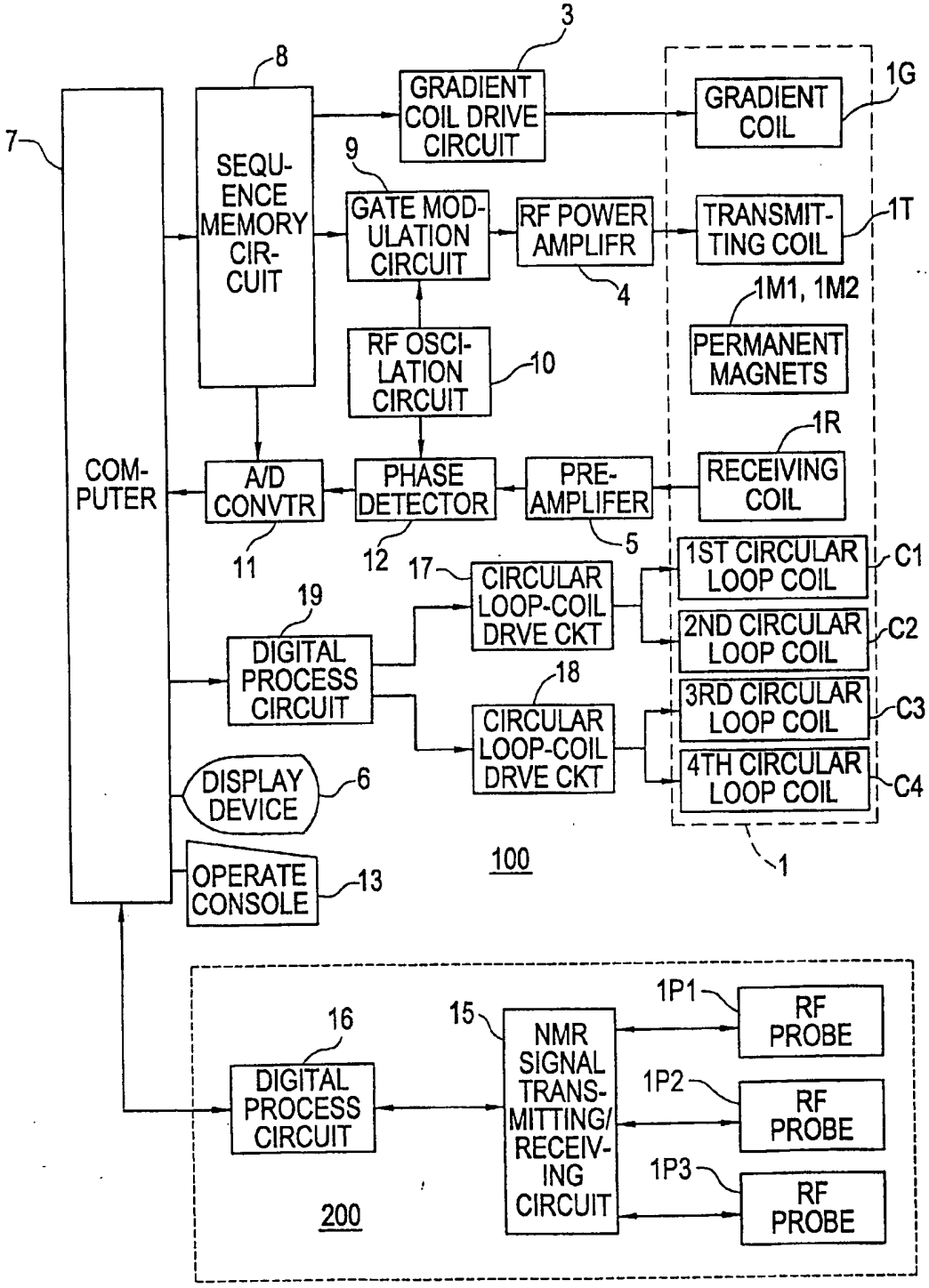

3
8
GRADIENT COIL DRIVE CIRCUIT
GRADIENT COIL
1G
7
SEQU-ENCE MEMORY CIR-CUIT
9
GATE MOD-ULATION CIRCUIT
RF POWER AMPLIFR
TRANSMIT-TING COIL
1T
4
1M1, 1M2
PERMANENT MAGNETS
RF OSCI-LATION CIRCUIT
10
1R
COM-PUTER
A/D CONVTR
PHASE DETECTOR
PRE-AMPLIFER
RECEIVING COIL
11
12
5
1ST CIRCULAR LOOP COIL
C1
17
CIRCULAR LOOP-COIL DRVE CKT
19
2ND CIRCULAR LOOP COIL
C2
DIGITAL PROCESS CIRCUIT
18
3RD CIRCULAR LOOP COIL
C3
CIRCULAR LOOP-COIL DRVE CKT
4TH CIRCULAR LOOP COIL
C4
DISPLAY DEVICE
6
100
1
OPERATE CONSOLE
13
1P1
RF PROBE
16
15
NMR SIGNAL TRANS-MITTING/ RECEIV-ING CIRCUIT
1P2
RF PROBE
DIGITAL PROCESS CIRCUIT
1P3
RF PROBE
200

FIG. 6

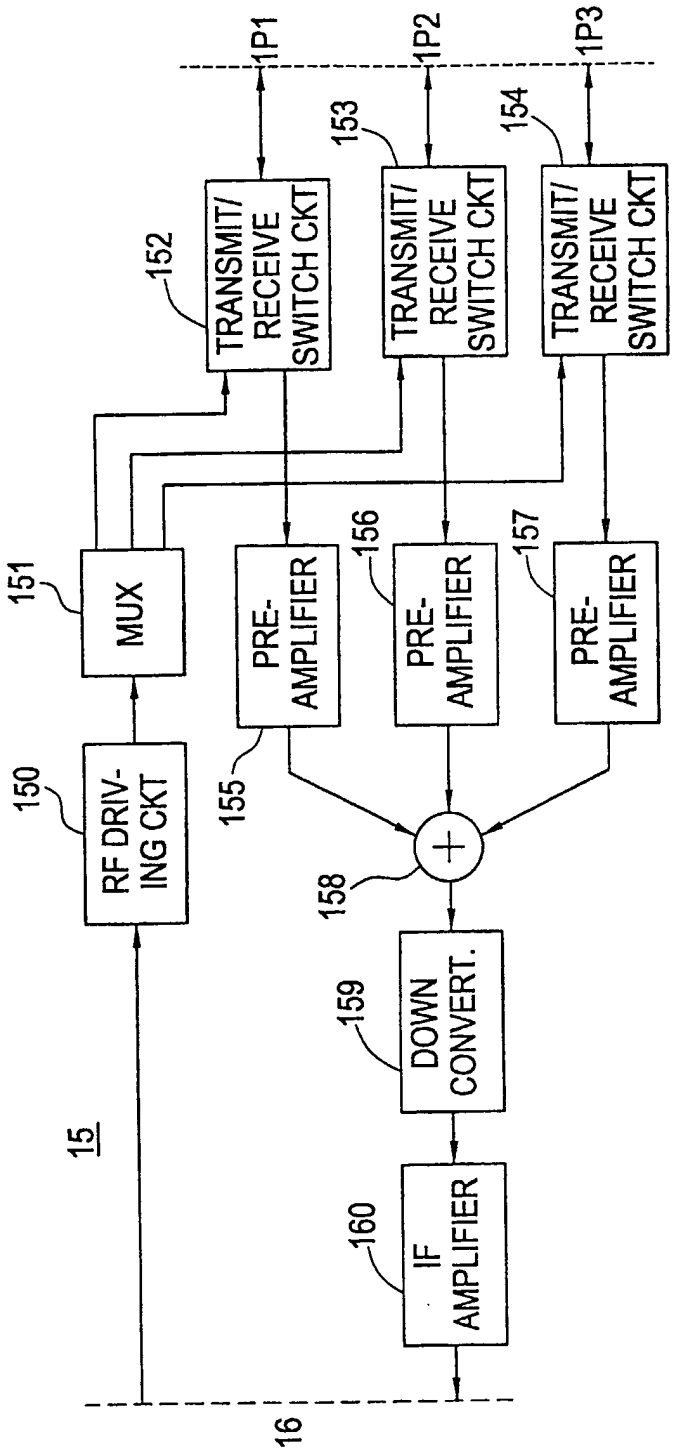

1P1
1P2
1P3
153
154
152
TRANSMIT/ RECEIVE SWITCH CKT
TRANSMIT/ RECEIVE SWITCH CKT
TRANSMIT/ RECEIVE SWITCH CKT
151
MUX
PRE-AMPLIFIER
156
PRE-AMPLIFIER
157
PRE-AMPLIFIER
150
RF DRIV-ING CKT
155
158
159
DOWN CONVERT.
15
160
IF AMPLIFIER
16

FIG. 7

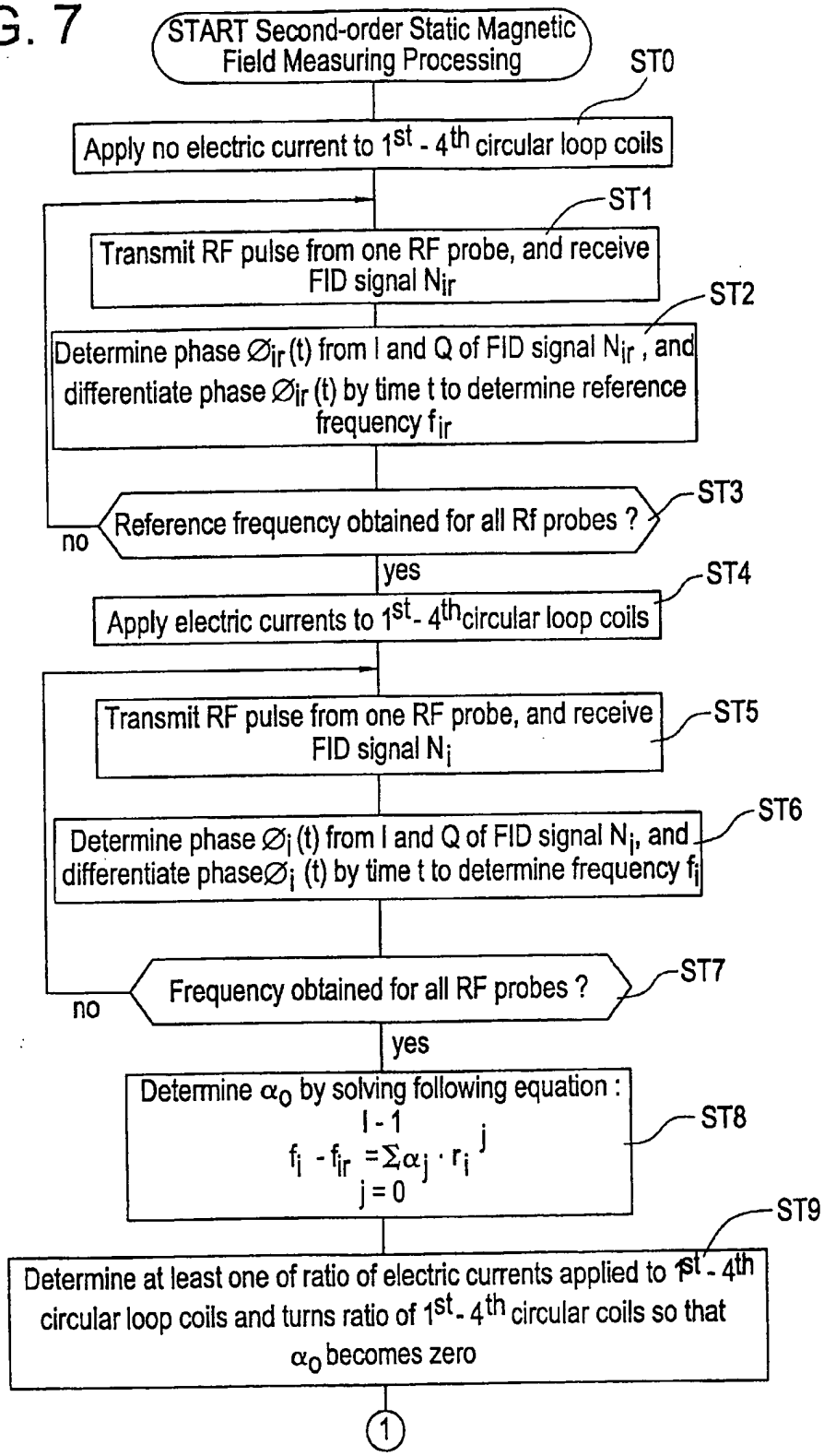

START Second-order Static Magnetic Field Measuring Processing
ST0
Apply no electric current to 1st - 4th circular loop coils
ST1
Transmit RF pulse from one RF probe, and receive FID signal Nir
ST2
Determine phase Øir (t) from I and Q of FID signal Nir , and differentiate phase Øir (t) by time t to determine reference frequency fir
ST3
Reference frequency obtained for all Rf probes ?
no
yes
ST4
Apply electric currents to 1st - 4th circular loop coils
Transmit RF pulse from one RF probe, and receive FID signal Ni
ST5
Determine phase Øi (t) from I and Q of FID signal Ni, and differentiate phase Øi (t) by time t to determine frequency fi
ST6
Frequency obtained for all RF probes ?
ST7
no
yes
Determine α0 by solving following equation :
fi - fir = Σ αj · ri^j (j = 0 to I - 1)
ST8
ST9
Determine at least one of ratio of electric currents applied to 1st - 4th circular loop coils and turns ratio of 1st - 4th circular coils so that α0 becomes zero
1

FIG. 8

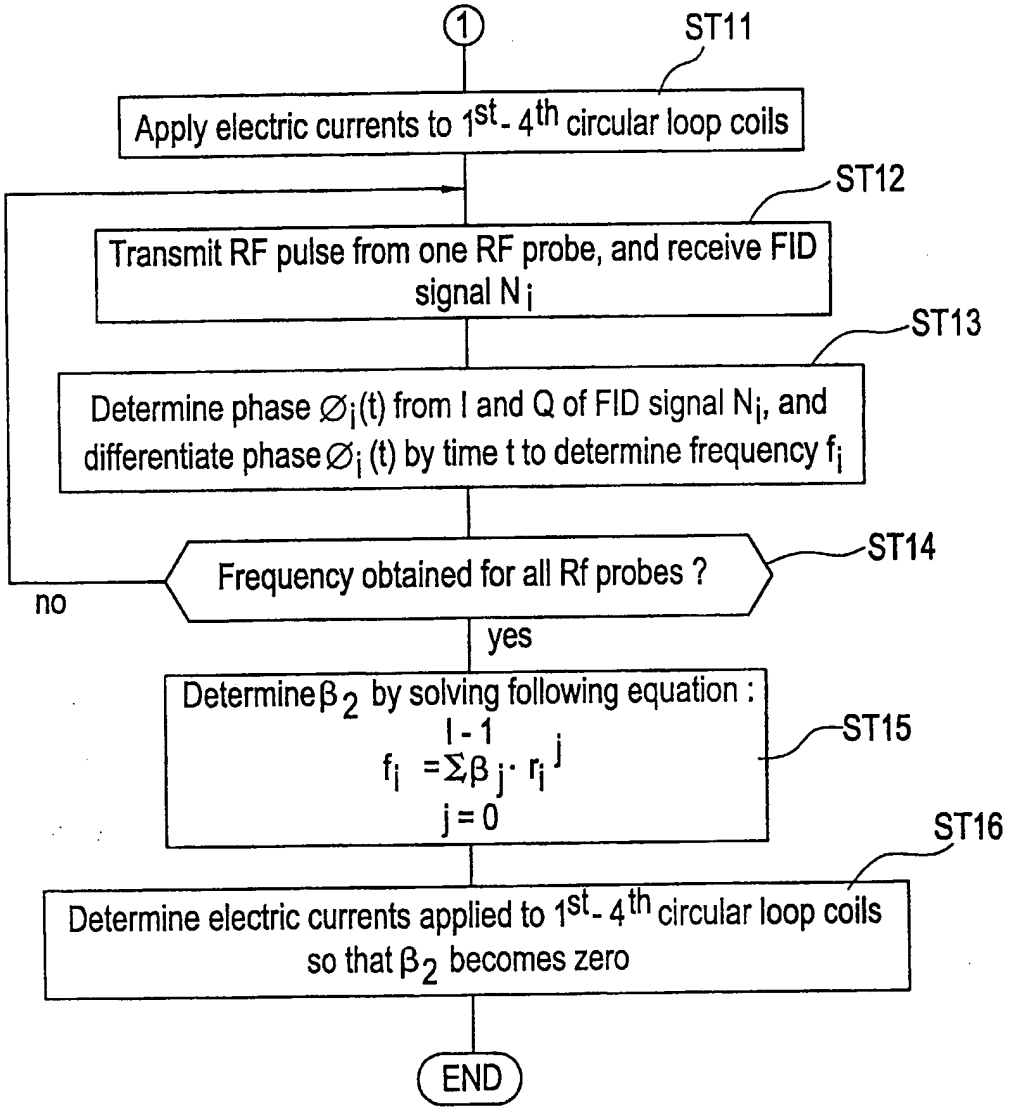

1
ST11
Apply electric currents to 1st - 4th circular loop coils
ST12
Transmit RF pulse from one RF probe, and receive FID signal N_i
ST13
Determine phase $\varnothing_i(t)$ from I and Q of FID signal N_i, and differentiate phase $\varnothing_i(t)$ by time t to determine frequency f_i
ST14
Frequency obtained for all Rf probes ?
no
yes
Determine β_2 by solving following equation :
$f_i = \sum_{j=0}^{I-1} \beta_j \cdot r_i^j$
ST15
ST16
Determine electric currents applied to 1st - 4th circular loop coils so that β_2 becomes zero
END

FIG. 9

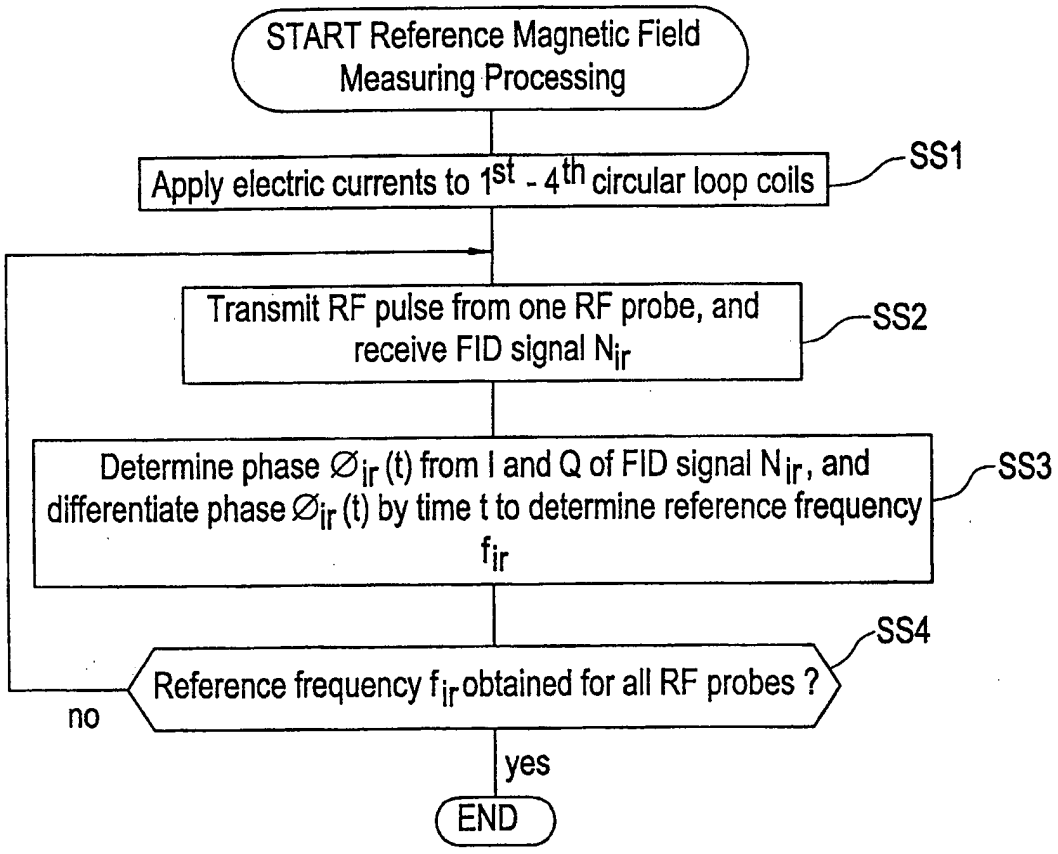
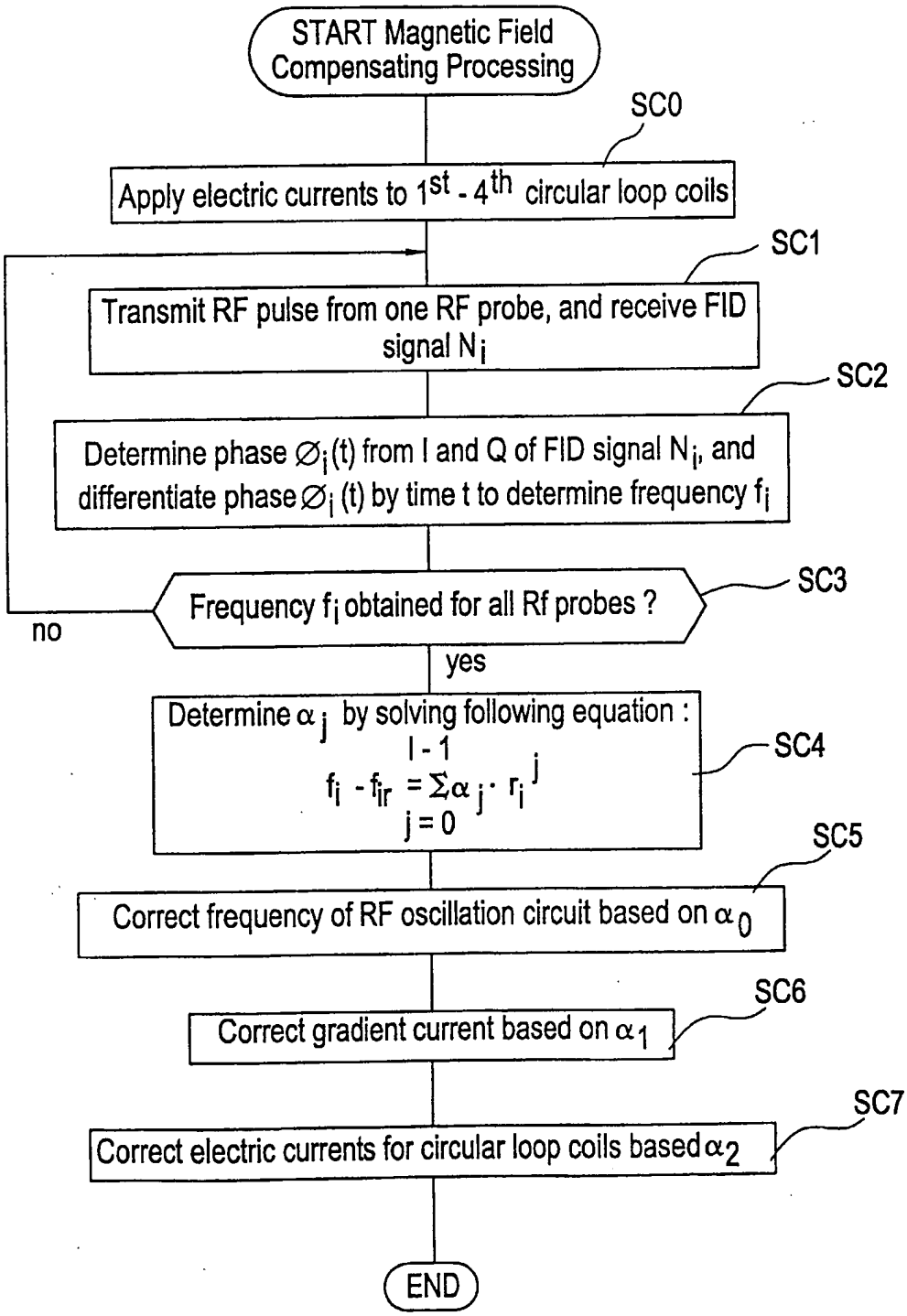

START Reference Magnetic Field Measuring Processing
Apply electric currents to 1st - 4th circular loop coils
SS1
Transmit RF pulse from one RF probe, and receive FID signal N_{ir}
SS2
Determine phase $\varnothing_{ir}(t)$ from I and Q of FID signal N_{ir}, and differentiate phase $\varnothing_{ir}(t)$ by time t to determine reference frequency f_{ir}
SS3
Reference frequency f_{ir} obtained for all RF probes ?
SS4
no
yes
END

FIG. 10


START Magnetic Field Compensating Processing
SC0
Apply electric currents to 1st - 4th circular loop coils
SC1
Transmit RF pulse from one RF probe, and receive FID signal N_i
SC2
Determine phase $\varnothing_i(t)$ from I and Q of FID signal N_i, and differentiate phase $\varnothing_i(t)$ by time t to determine frequency f_i
SC3
Frequency f_i obtained for all Rf probes ?
no
yes
Determine α_j by solving following equation :
$f_i - f_{ir} = \sum_{j=0}^{l-1} \alpha_j \cdot r_i^j$
SC4
SC5
Correct frequency of RF oscillation circuit based on α_0
SC6
Correct gradient current based on α_1
SC7
Correct electric currents for circular loop coils based α_2
END